Analyzing Physics-Dynamics Coupling in an Ensemble of Simplified GCMs

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Organizing team

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What is DCMIP?

DCMIP: 2-week summer school and Dynamical Core Model Intercomparison Project (DCMIP): 2008, 2012, 2016
in 2016: use **idealized moist test cases** and focus on non-hydrostatic dynamical cores and their physics-dynamics coupling

Three "core" test cases with idealized physics processes:
- **Test 1: Dry and moist (Kessler-physics) baroclinic instability test with "toy" terminator chemistry** (110 km, 30 vertical levels)
- **Test 2:** Moist tropical cyclone test
- **Test 3:** Moist mesoscale storm test (supercell)

Recent paper: "DCMIP2016: a review of non-hydrostatic dynamical core design and intercomparison of participating models", Ullrich et al. (2017) in GMD

"Living" Test case document and DCMIP-2016 web page:
https://github.com/ClimateGlobalChange/DCMIP2016
https://www.earthsystemcog.org/projects/dcmip-2016/

Warm-Rain Kessler Physics Scheme

Potential temperature

$$\frac{\Delta\theta}{\Delta t} = \frac{L}{c_p\pi}\left(\frac{\Delta q_{vs}}{\Delta t} - E_r\right)$$

vapor

$$\frac{\Delta q_v}{\Delta t} = -\frac{\Delta q_{vs}}{\Delta t} + E_r$$

cloud water

$$\frac{\Delta q_c}{\Delta t} = \frac{\Delta q_{vs}}{\Delta t} - A_r - C_r$$

rain water

$$\frac{\Delta q_r}{\Delta t} = -E_r + A_r + C_r - V_r\frac{\partial q_r}{\partial z}$$

3 prognostic hydrometeors

Condensation

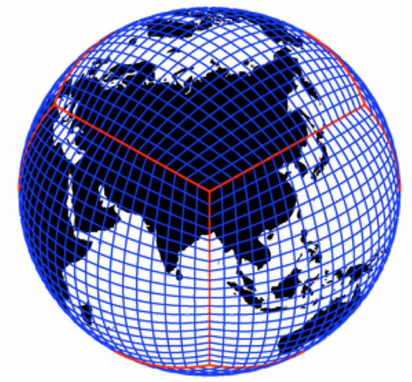
Rain water evaporation

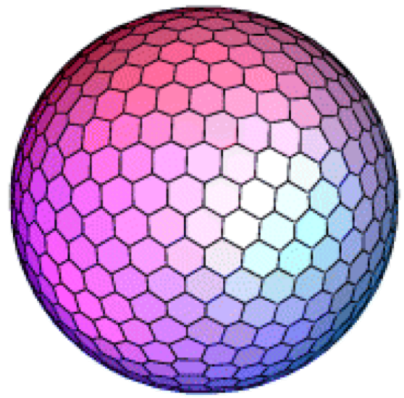
Auto-conversion

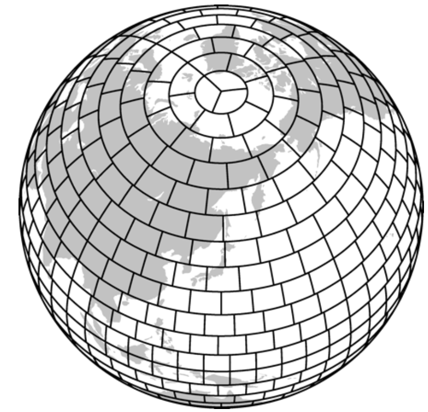
Collection rate of rain water

Precipitation

DCMIP-2016 Models (in blue: comparison models)



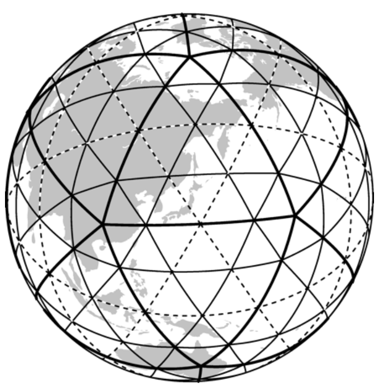


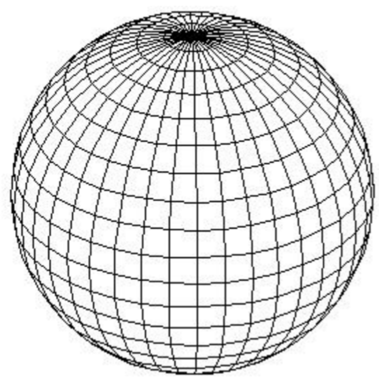


- ACME (E3SM) (DoE, CU)
- FV3 (GFDL)
- Tempest (UC Davis)
- CAM SE (NCAR), hydrost.

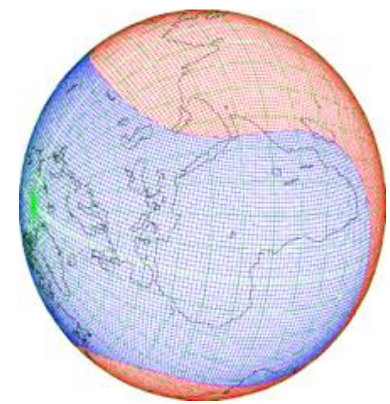
- CSU_LZ (CSU)
- OLAM (U. Miami)
- NICAM (Riken, U. Tokyo)
- MPAS (NCAR)

- FVM (ECMWF)





- CAM FV (NCAR), hydrostatic

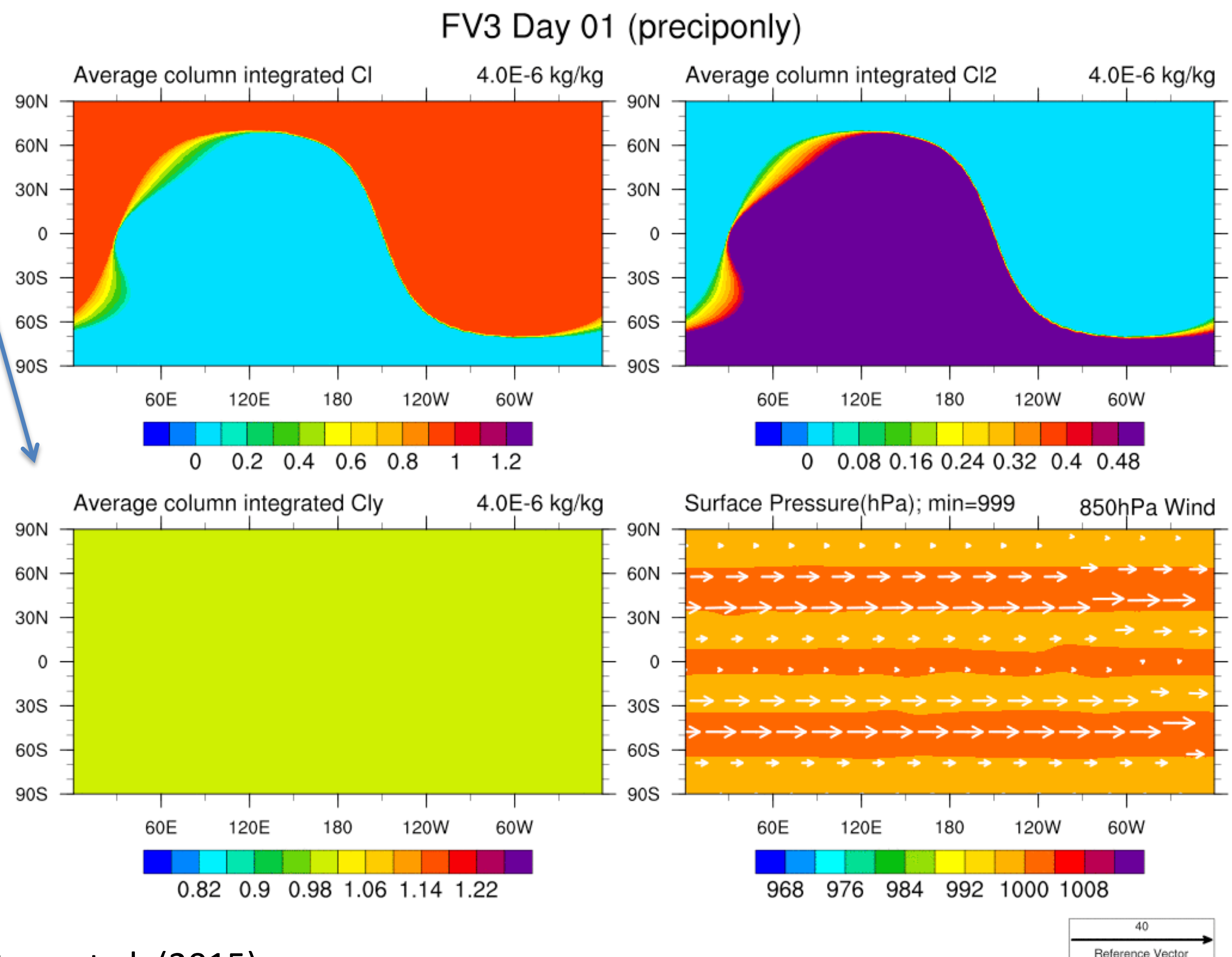


- GEM (Environment Canada)

- ICON (DWD & MPI, Germany)
- DYNAMICO (LMD, IPSL, France), hydrostatic

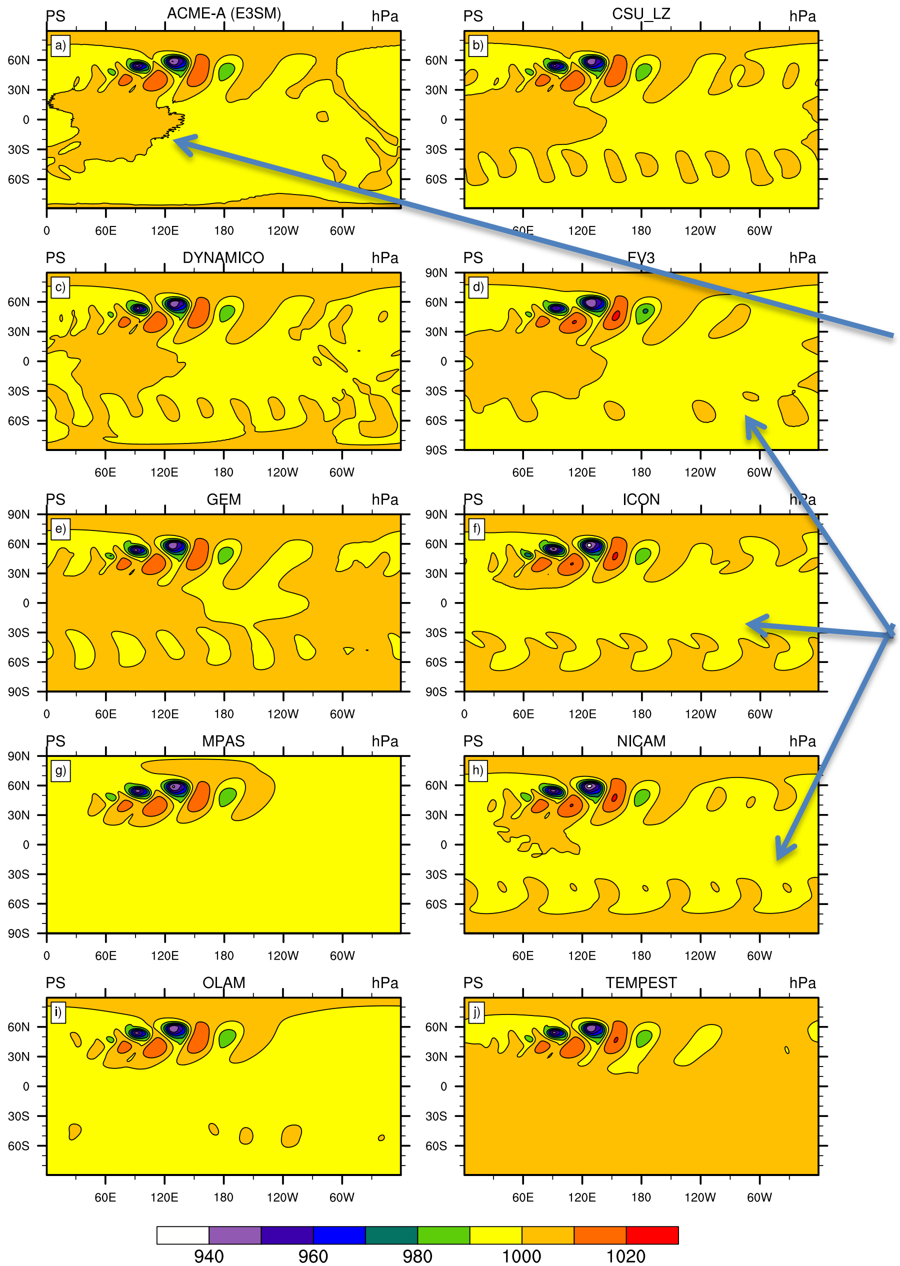
DCMIP-2016 Snapshots: "Toy" Terminator Chemistry

Tracer advection test with correlated tracers: Cly is the sum of Cl and Cl2 (needs to stay constant)



Lauritzen et al. (2015)

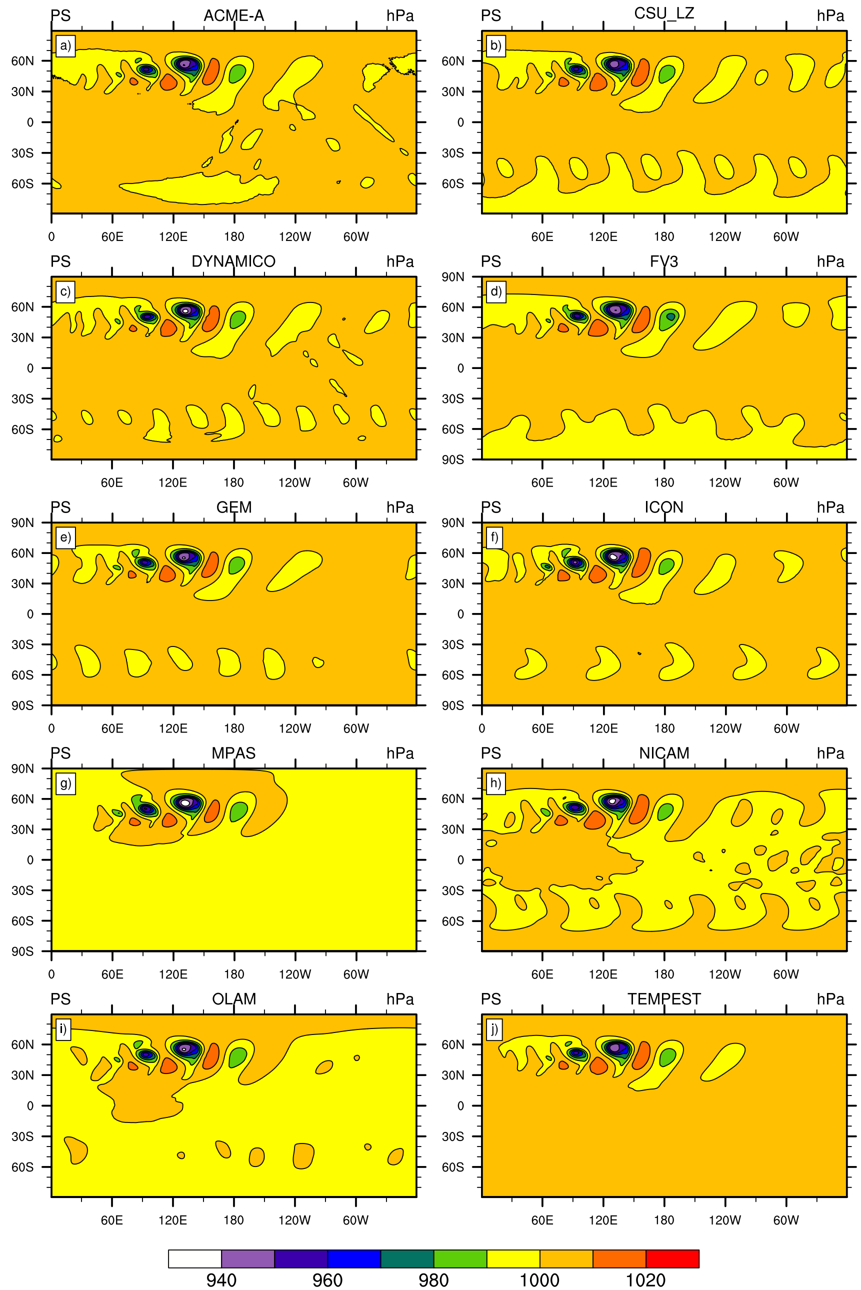
Snapshots of the dry baroclinic wave



Surface pressure at day 10 (Δx=110 km): overall patterns similar, details differ

- Some Gibb's ringing in ACME (spectral element model)
- Some grid imprinting (wave 4 and wave 5 signals) in CSU_LZ, DYNAMICO, FV3, ICON, NICAM, apparent in the Southern Hemispheres

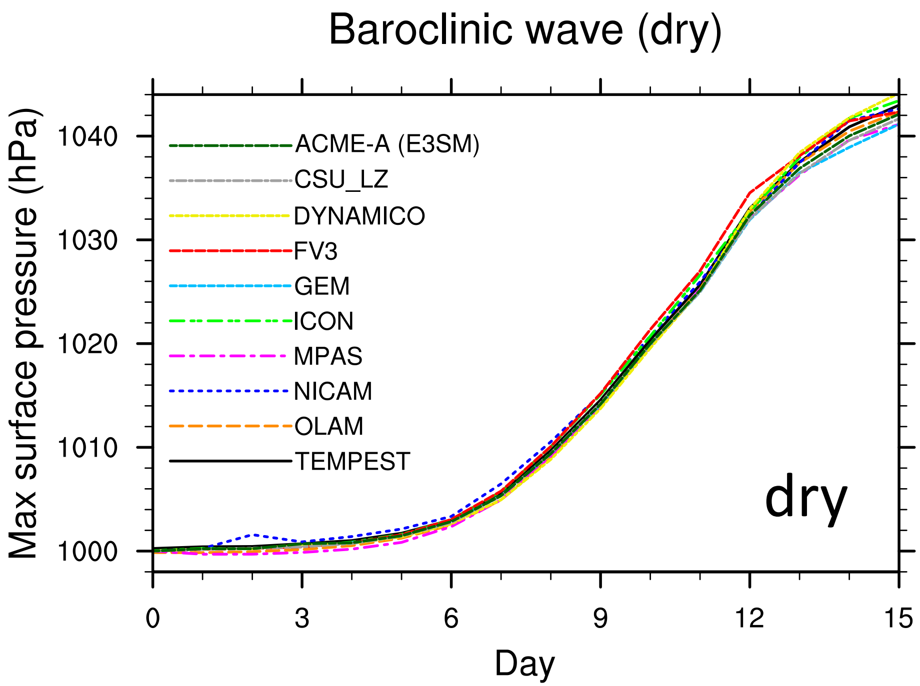
Snapshots of the moist baroclinic wave

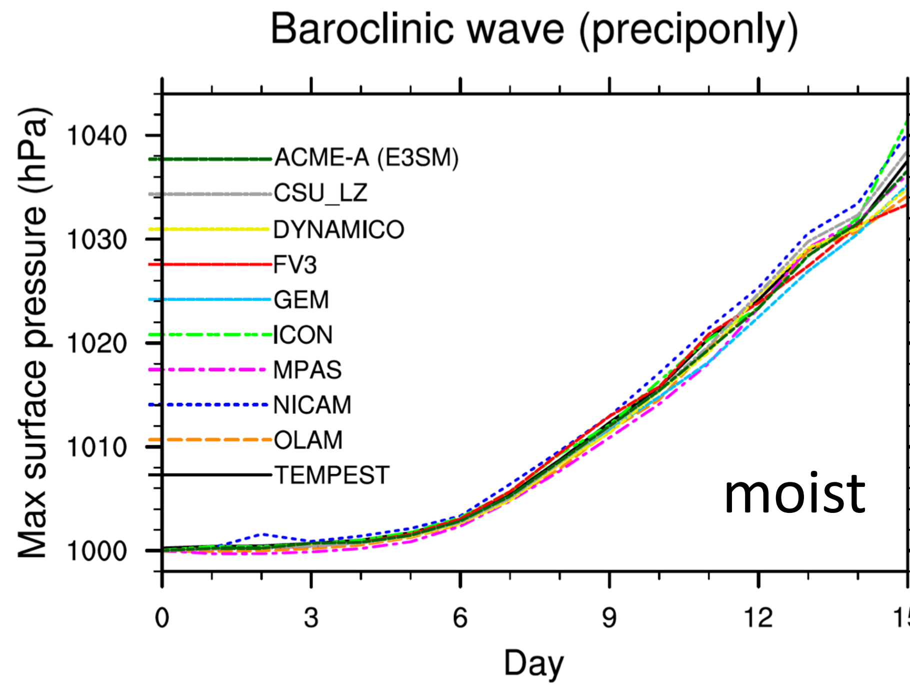


Surface pressure at day 10 (Δx=110 km): overall patterns similar, details differ

- Patterns look almost identical to the dry surface pressure patterns
- Moisture effects weaken high pressure systems and strengthen low pressure systems (e.g. visible in ICON and MPAS)

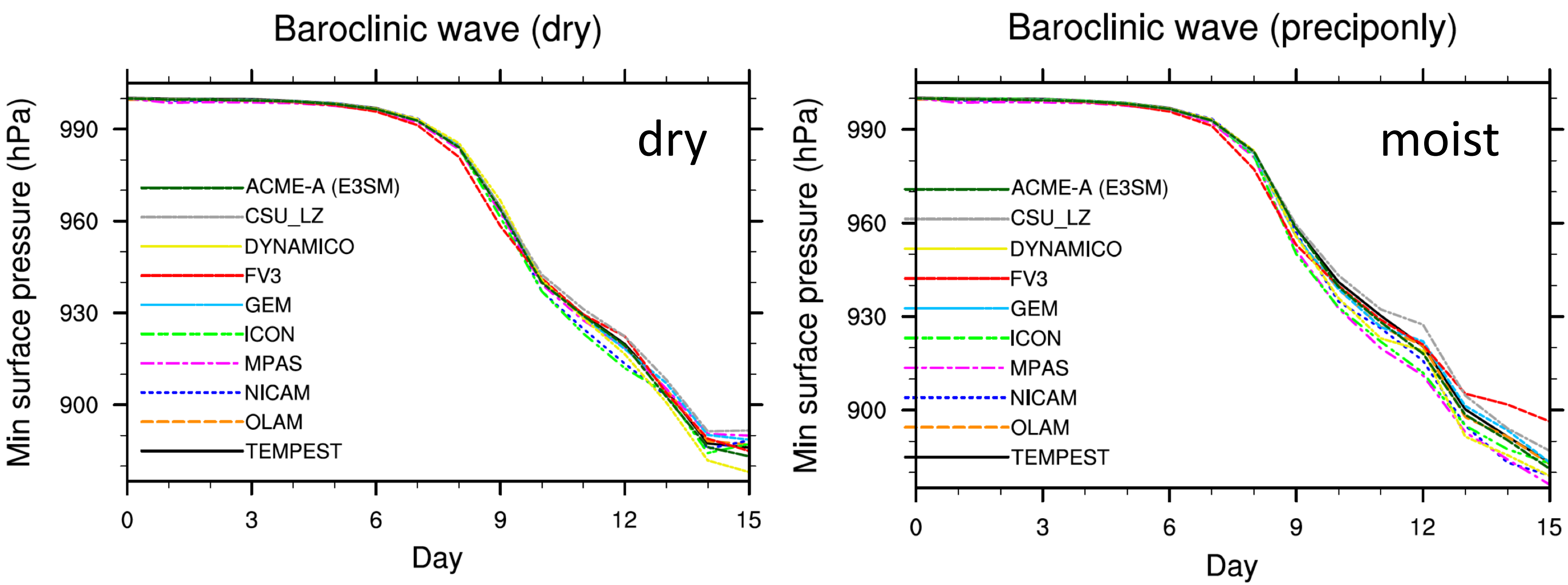
15-Day Time Series: dry and moist ps maxima





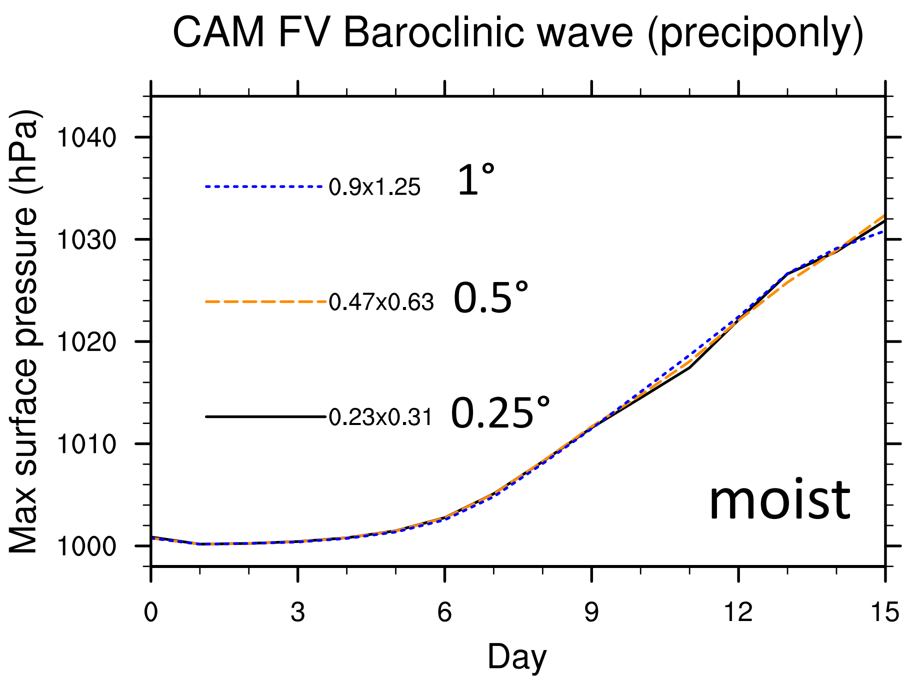
- Moisture effects **weaken high pressure** systems
- Presence of moisture **widens the ensemble spread** early in the simulations
- Points to the uncertainties in the physics-dynamics interactions and the possible impact of effective resolutions

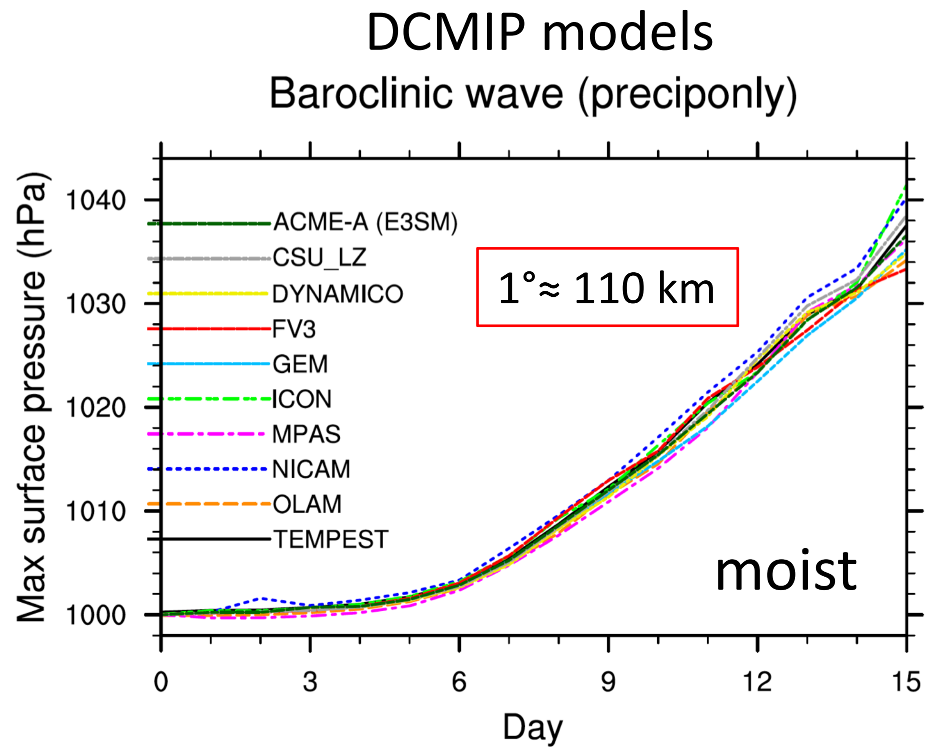
15-Day Time Series: dry and moist ps minima



- Moisture effects: slight **tendency to strengthen low pressure** systems
- Presence of moisture **considerably widens the ensemble spread**
- Models tend to diverge after day 12

Impact of Resolution: Moist ps maxima

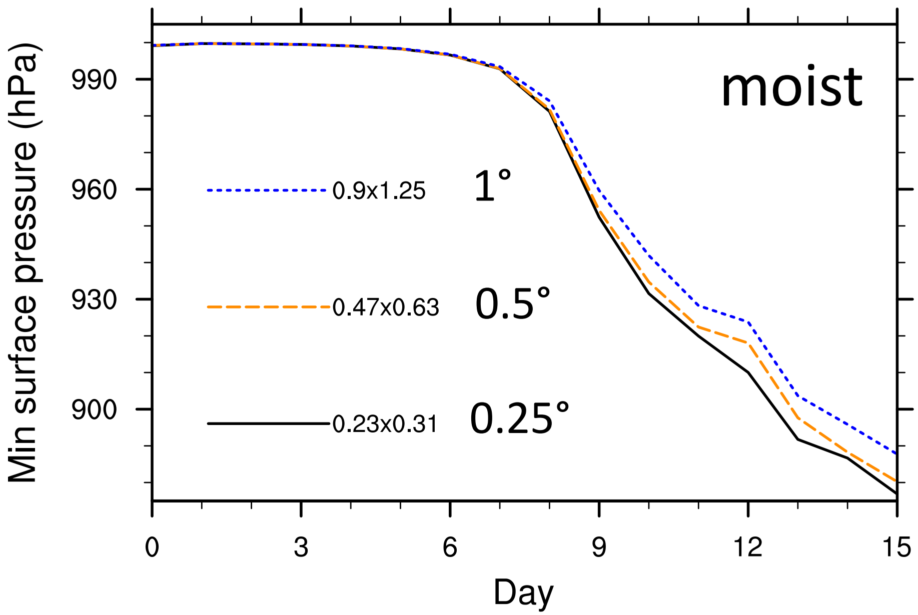




- Impact of the horizontal resolution on the evolution of the surface pressure maxima is small (in moist CAM FV, similar to FV3 model)
- However, PS_{min} spread in DCMIP models increases (next slide), physics-dynamics interactions most apparent in low pressure regions with precipitation and updraft

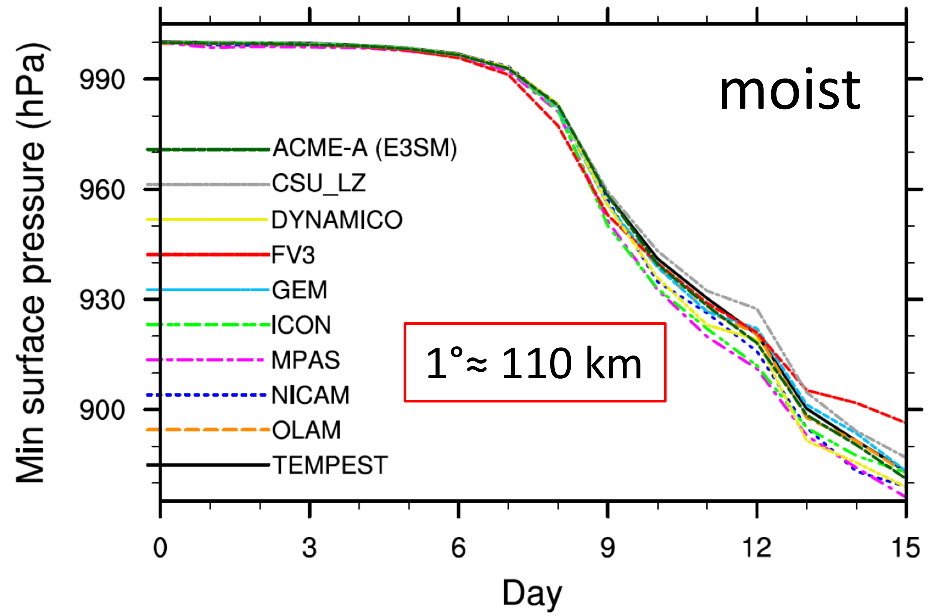
Impact of Resolution: Moist ps minima

CAM FV Baroclinic wave (preciponly)



DCMIP models

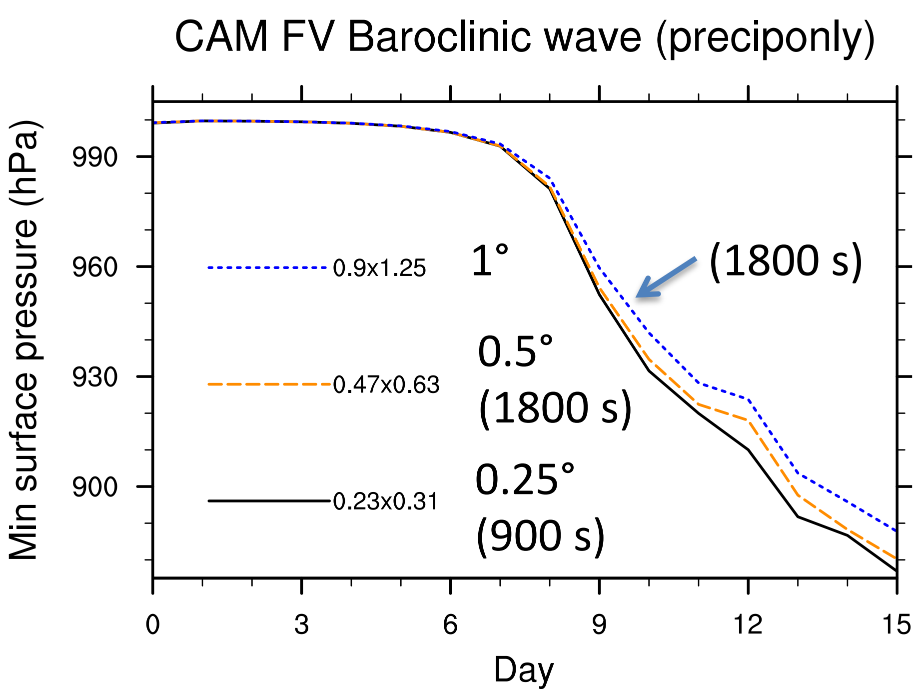
Baroclinic wave (preciponly)

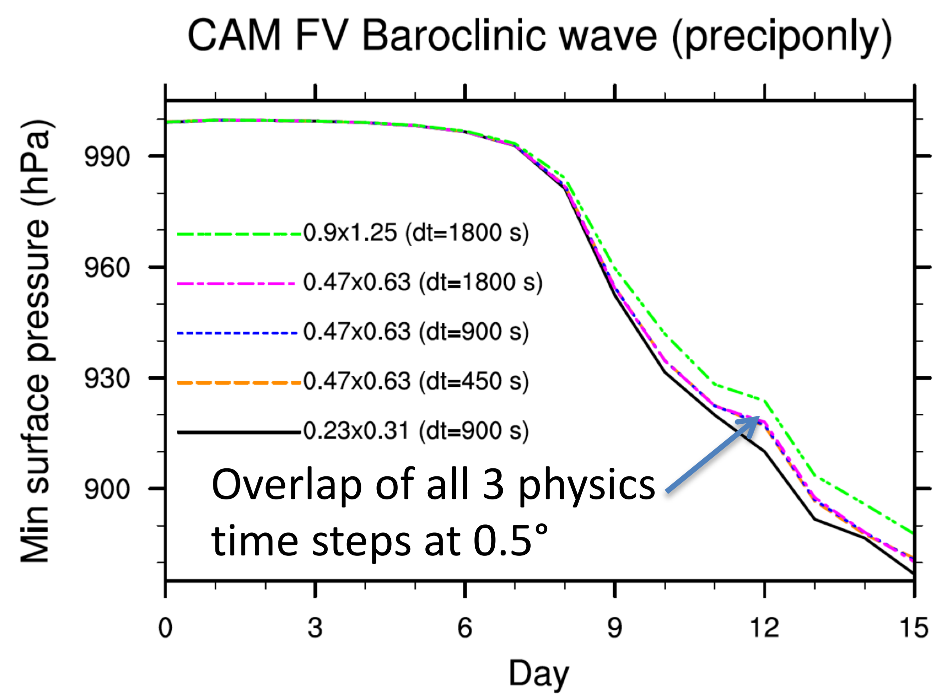


- **Increasing the horizontal resolutions** from 1° (110 km) to 0.5° /0.25° (55/28 km) **strengthens the surface pressure minima** in moist CAM FV
- Possible pathway: high precipation rates force intensification
- PS_{min} spread in DCMIP models includes the effects of the effective resolutions

Impact of Physics time step: Moist ps minima

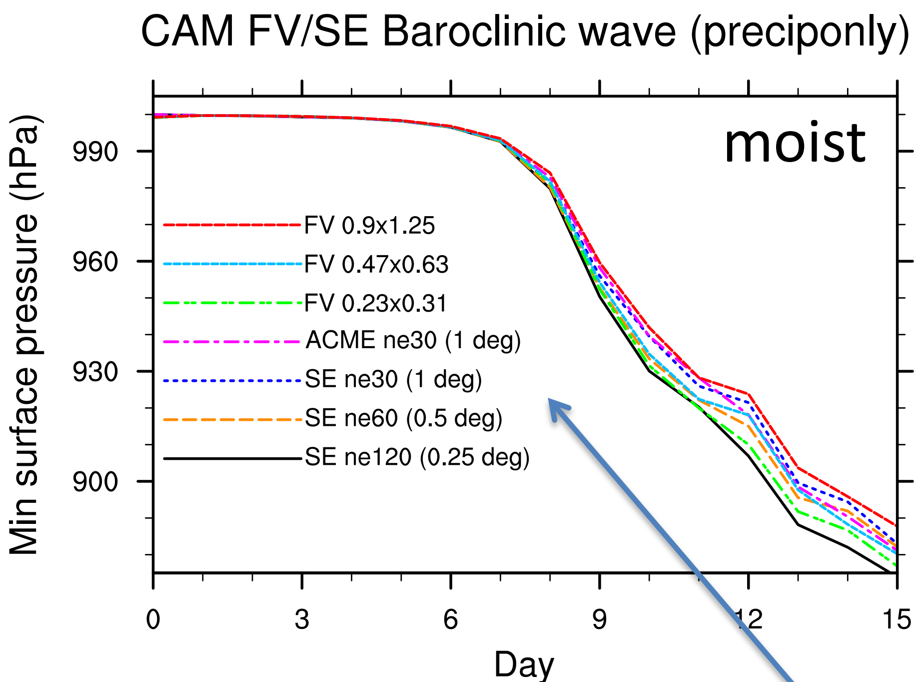
Increased resolutions often come with decreased physics time steps

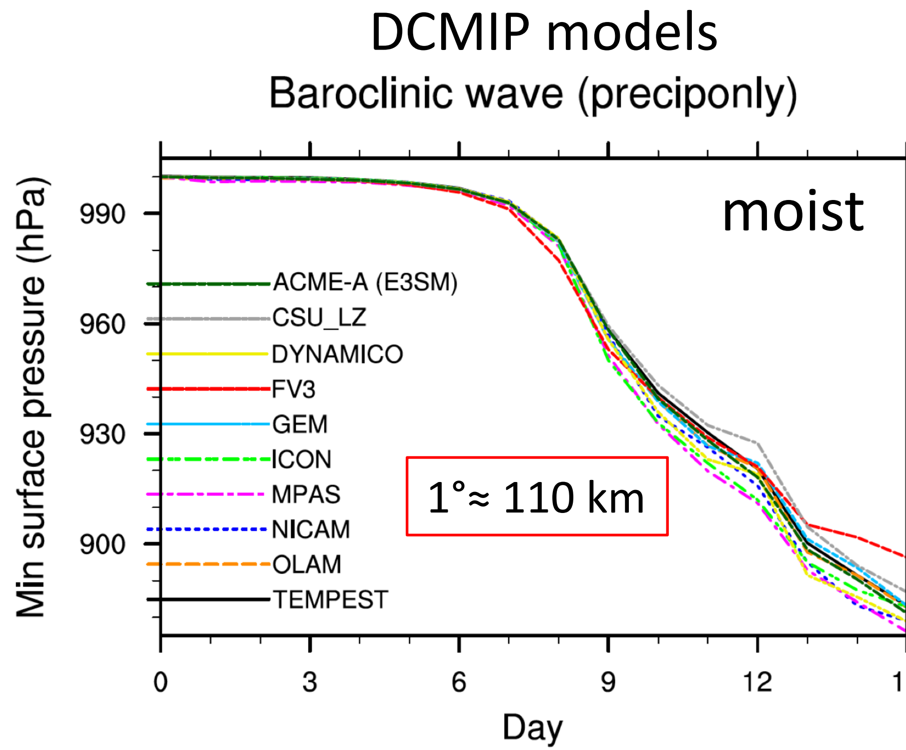




- **Varying the physics time step** from 1800 s, 900 s to 450 s has **very little impact** on the minimum surface pressure evolution in CAM FV(0.5°)
- Suggests that physics time step is not the main driver for the model differences among DCMIP models

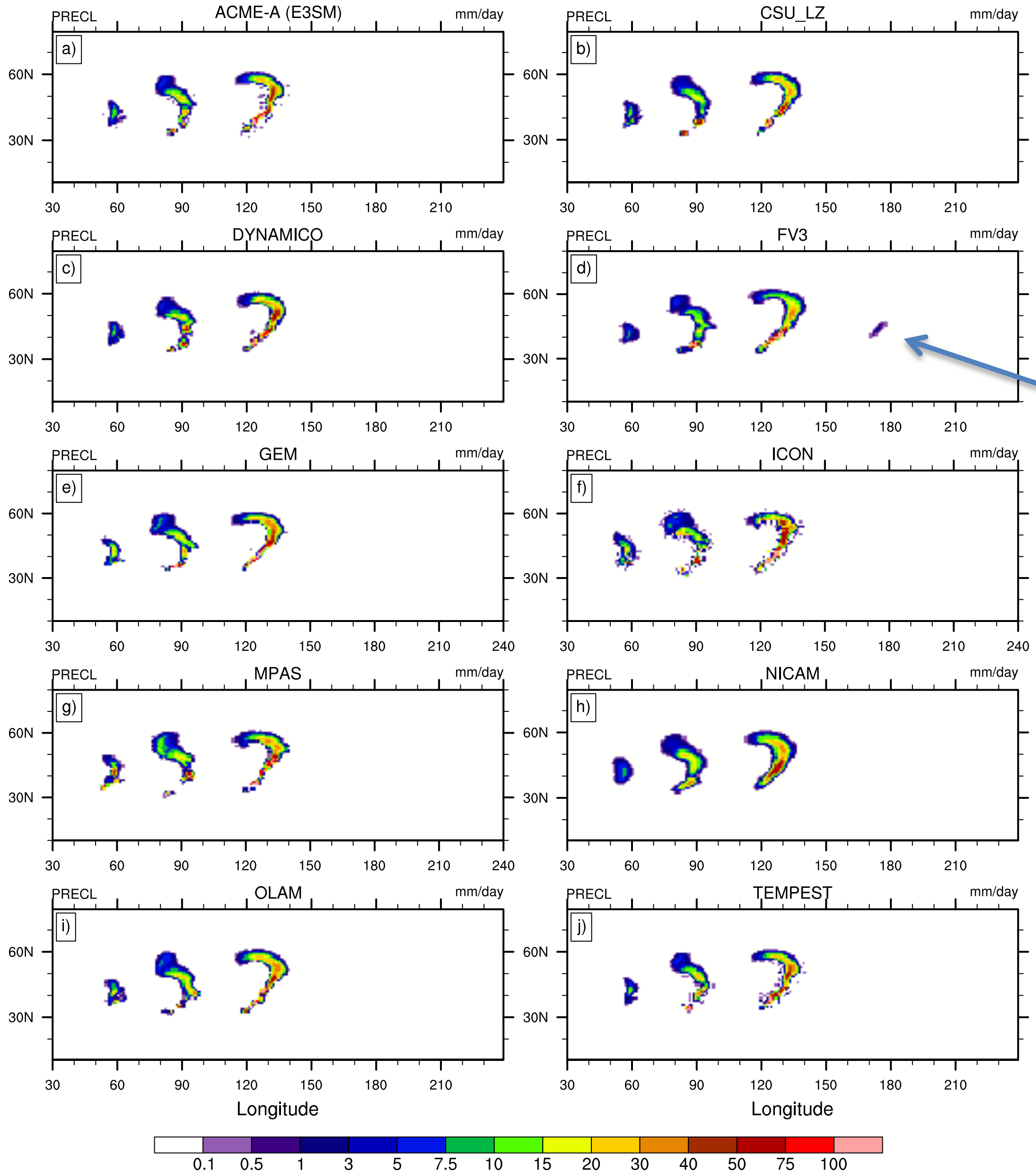
Impact of Model Design & Resolution: Moist ps_{min}





- **Increasing the horizontal resolutions** from 1° (110 km) to 0.5° /0.25° (55/28 km) **strengthens the surface pressure minima** in CAM FV and CAM SE
- PS_{min} spread in DCMIP models includes the effects of the effective resolutions and coupling uncertainties

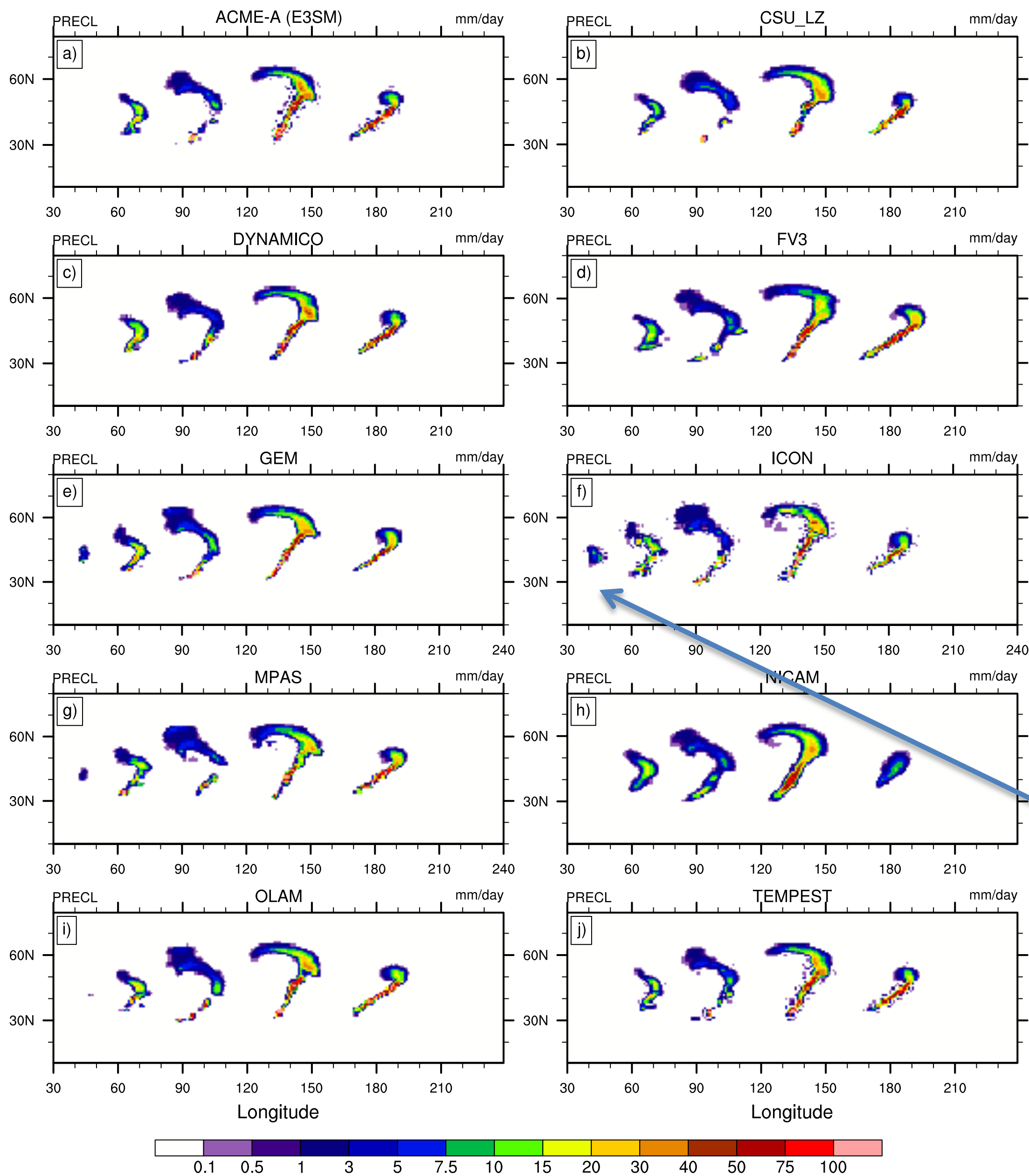
Precipitation rates in the moist baroclinic wave



Precipitation rates at day 9 (Δx=110 km): overall patterns similar, details differ

- FV3 strengthens the fastest, already shows 4th precipitation band
- Differing levels of 'noise' (broken contours) and diffusion in the precipitation bands are apparent

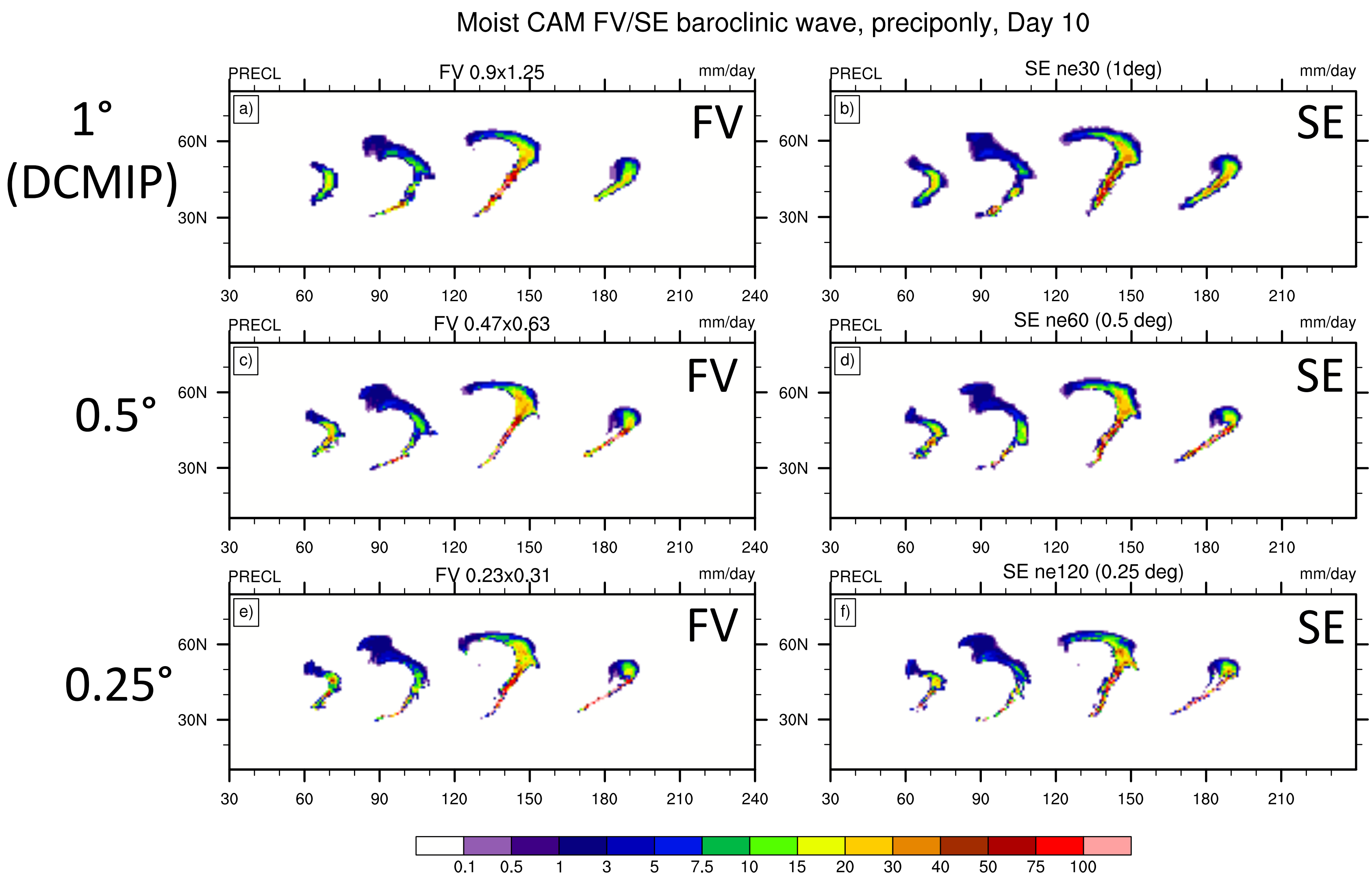
Precipitation rates in the moist baroclinic wave



Precipitation rates at day 10 (Δx=110 km): overall patterns similar, details differ

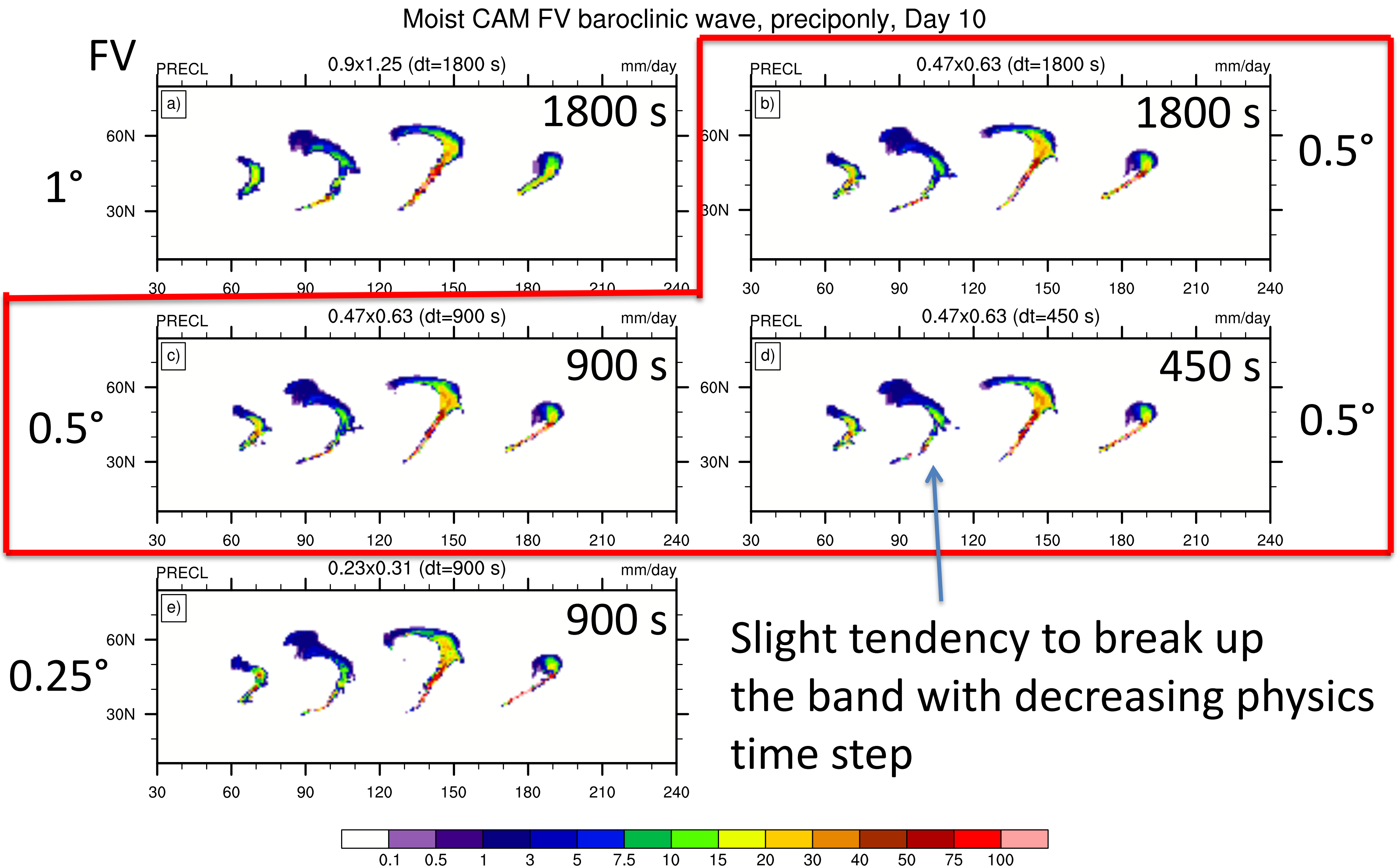
- At day 10 precipitation bands become very narrow, tend to break up in some models (with very strong grid-point scale precipitation)
- 3 models already develop 5th precipitation band

Precipitation rates: Impact of Resolution



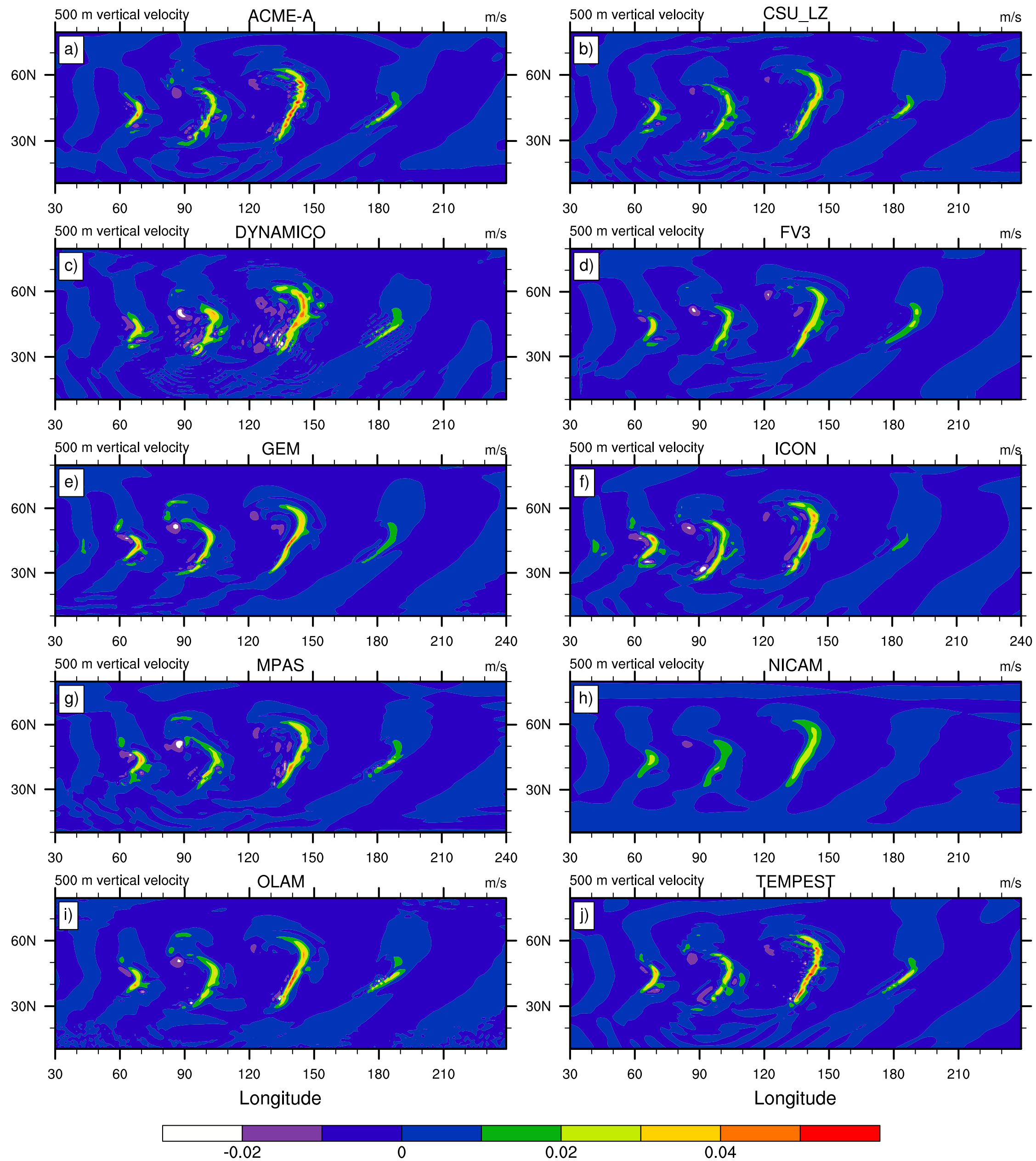
- Increasing horizontal resolution sharpens the precipitation patterns and increases the peaks in CAM FV and CAM SE

Precipitation rates: Impact of Physics Time Step



- Physics time steps in CAM FV have little effect on patterns

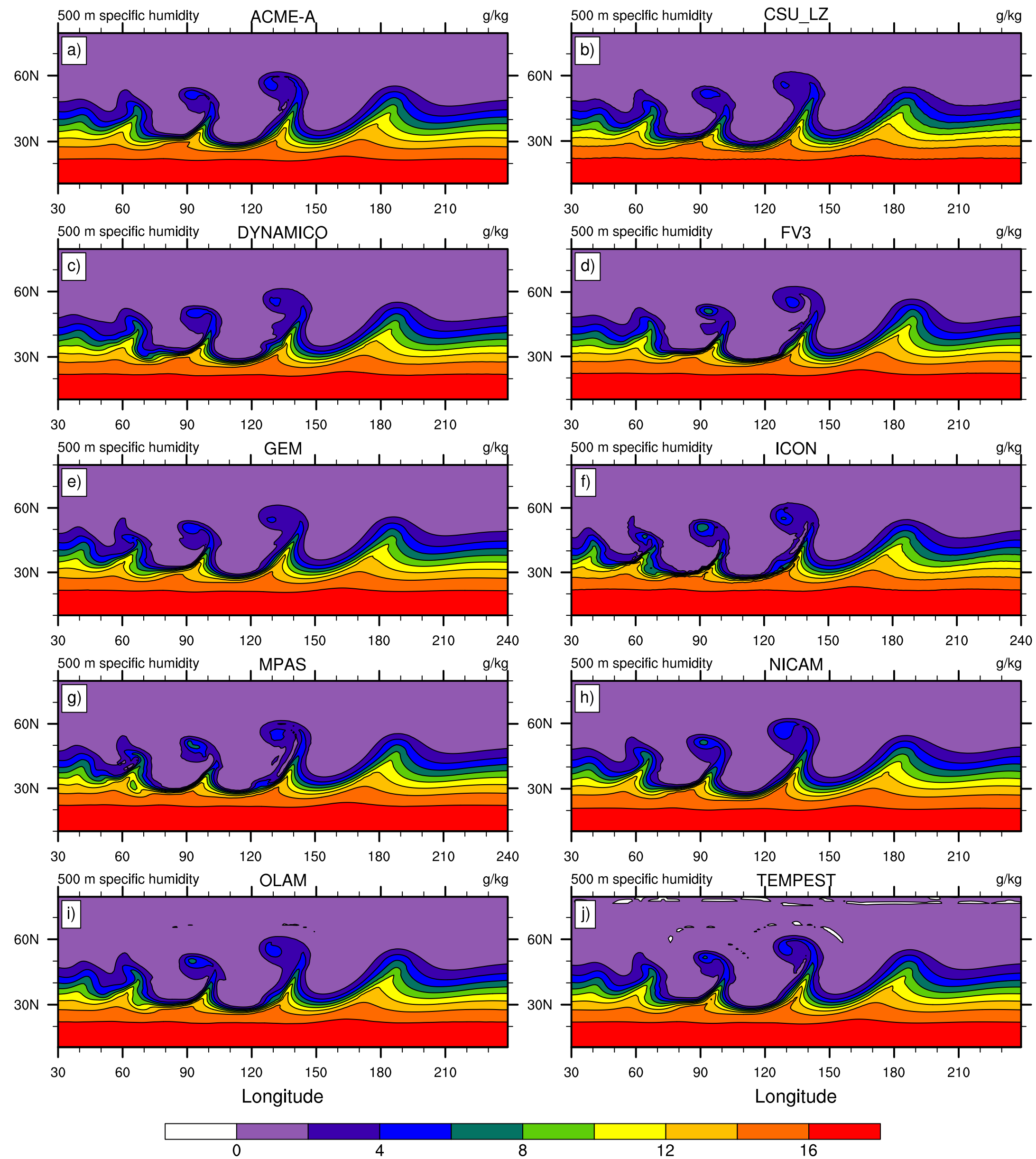
Vertical velocity in the moist baroclinic wave



500 m vertical velocity at day 10 (Δx=110 km): overall patterns similar, details differ

- Precipitation bands tightly connected to the narrow updraft areas
- Reduced updrafts translate into reduced precipitation rates
- Noisy updraft areas lead to noise in precipitation rates

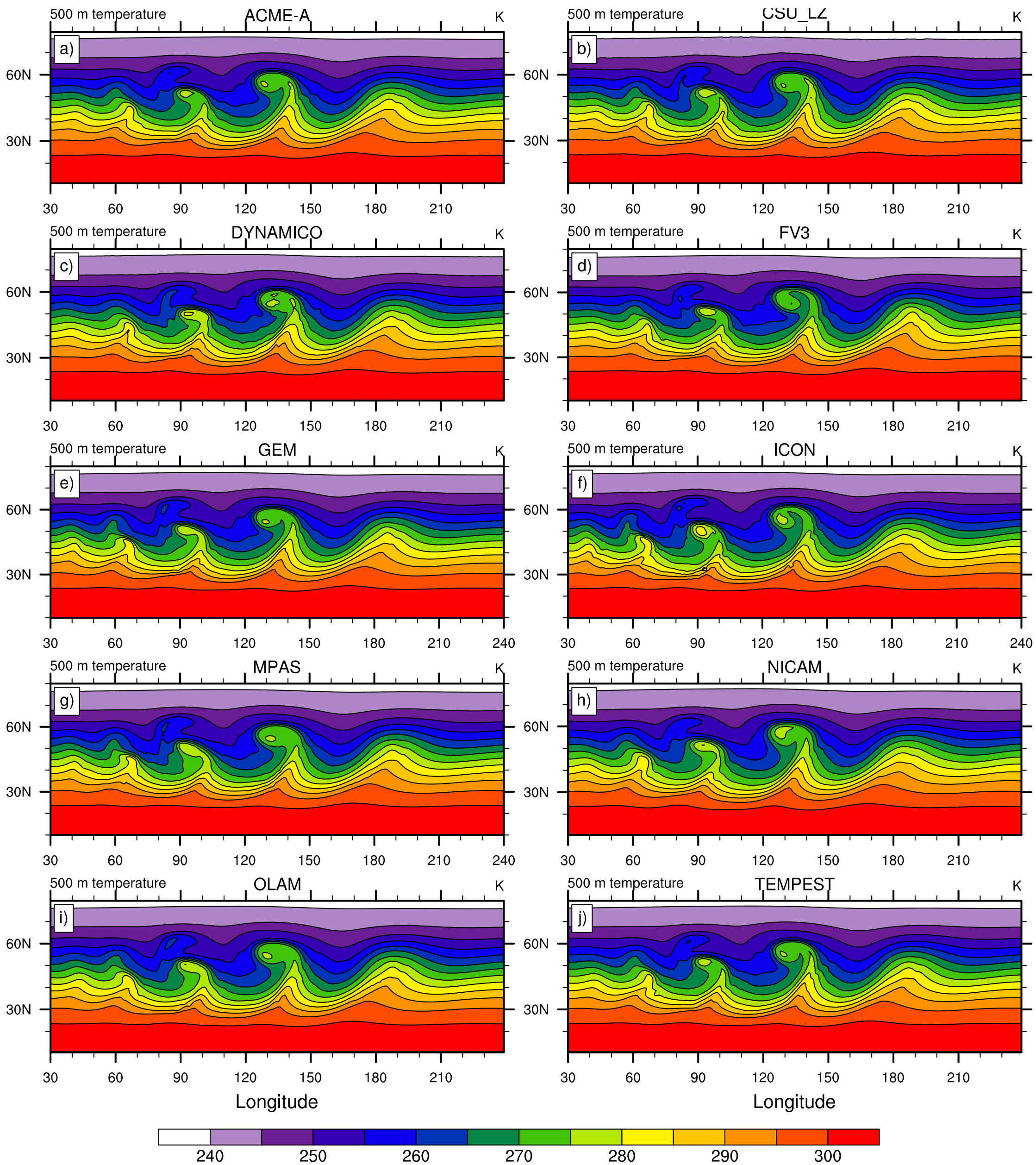
Specific humidity in the moist baroclinic wave



500 m specific humidity at day 10 (Δx=110 km): overall patterns similar, details differ

- High levels of specific humidity are advected from the moist tropical areas into the midlatitudes (ahead of the low pressure systems)
- Specific humidity provides moisture source for the Kessler precipitation scheme

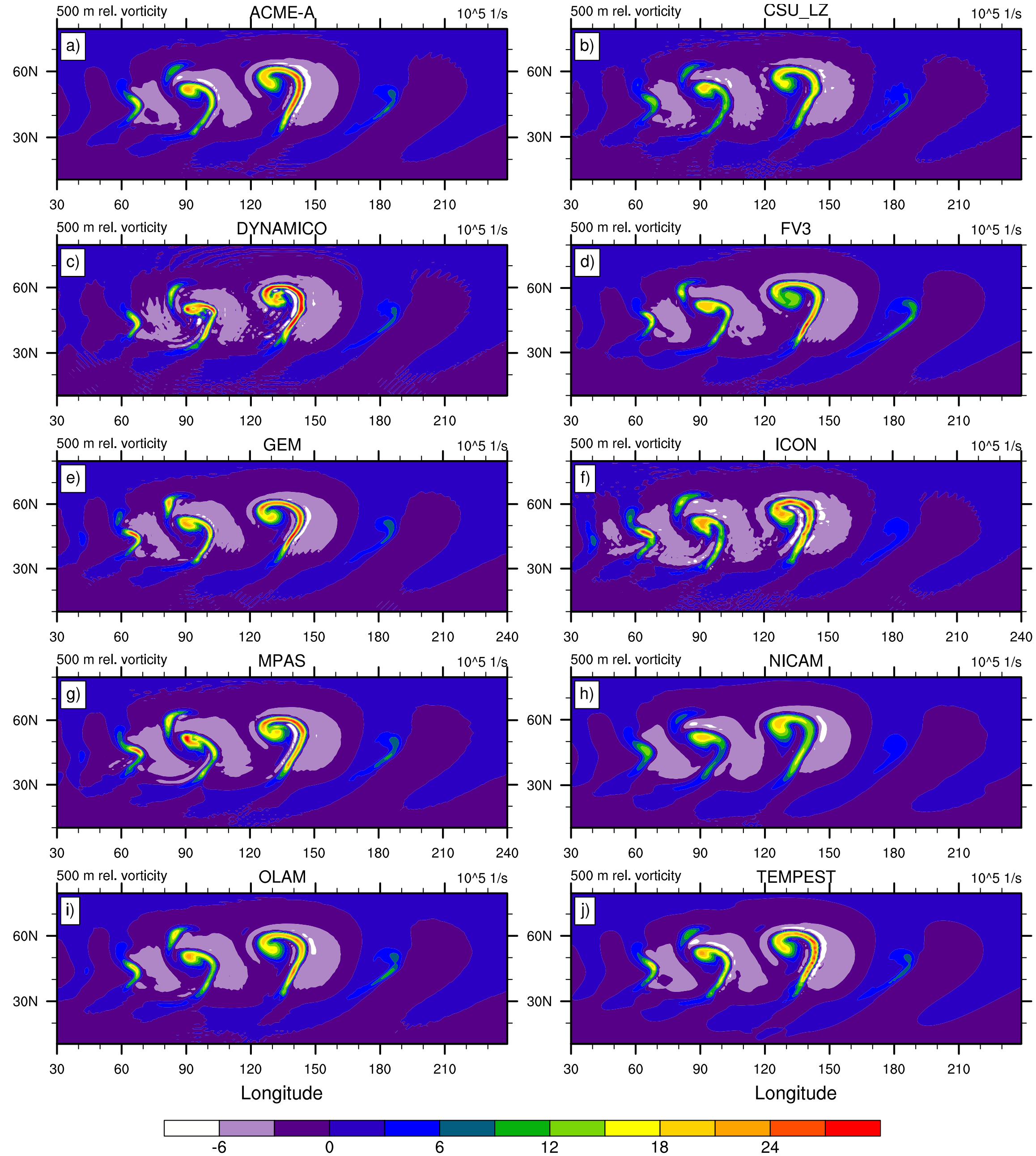
Temperature in the moist baroclinic wave



500 m temperature at day 10 (Δx=110 km): overall patterns similar, details differ

- Breaking waves at day 10 (also visible in the specific humidity field)
- Updrafts are connected to the strong temperature fronts

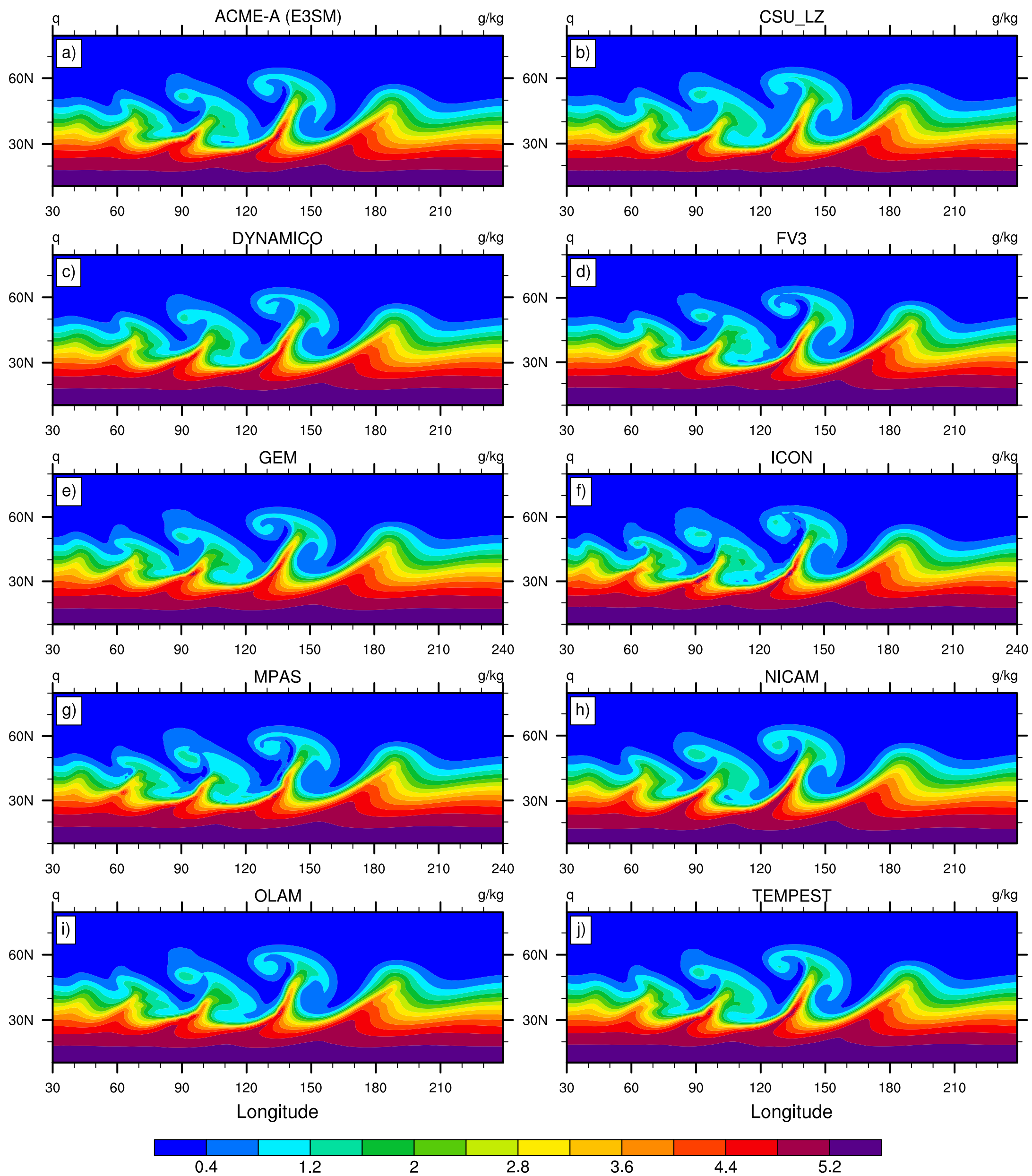
Relative vorticity in the **moist** baroclinic wave



500 m relative vorticity at day 10 (Δx=110 km): overall patterns similar, details differ

- Maxima and minima differ (by about 30%) and are found in very narrow strips (challenges the 110 km grid spacing)
- Vorticity highlights noise and the diffusive properties of the model

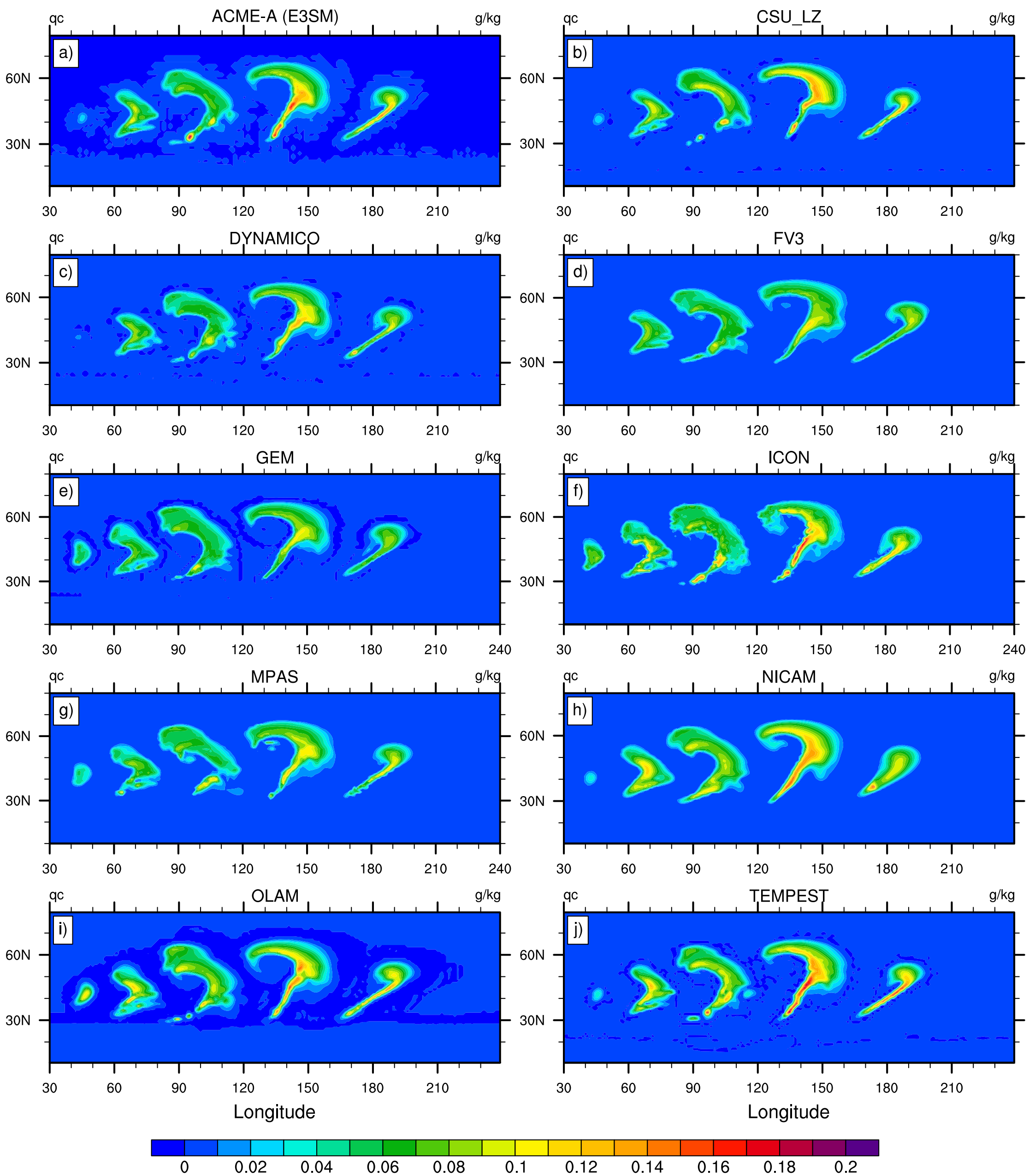
Integrated water vapor: moist baroclinic wave



Vertically integrated water vapor at day 10 (Δx=110 km): overall patterns similar, only details differ

- Seems to be predicted rather well, field is dominated by large-scale resolved advection

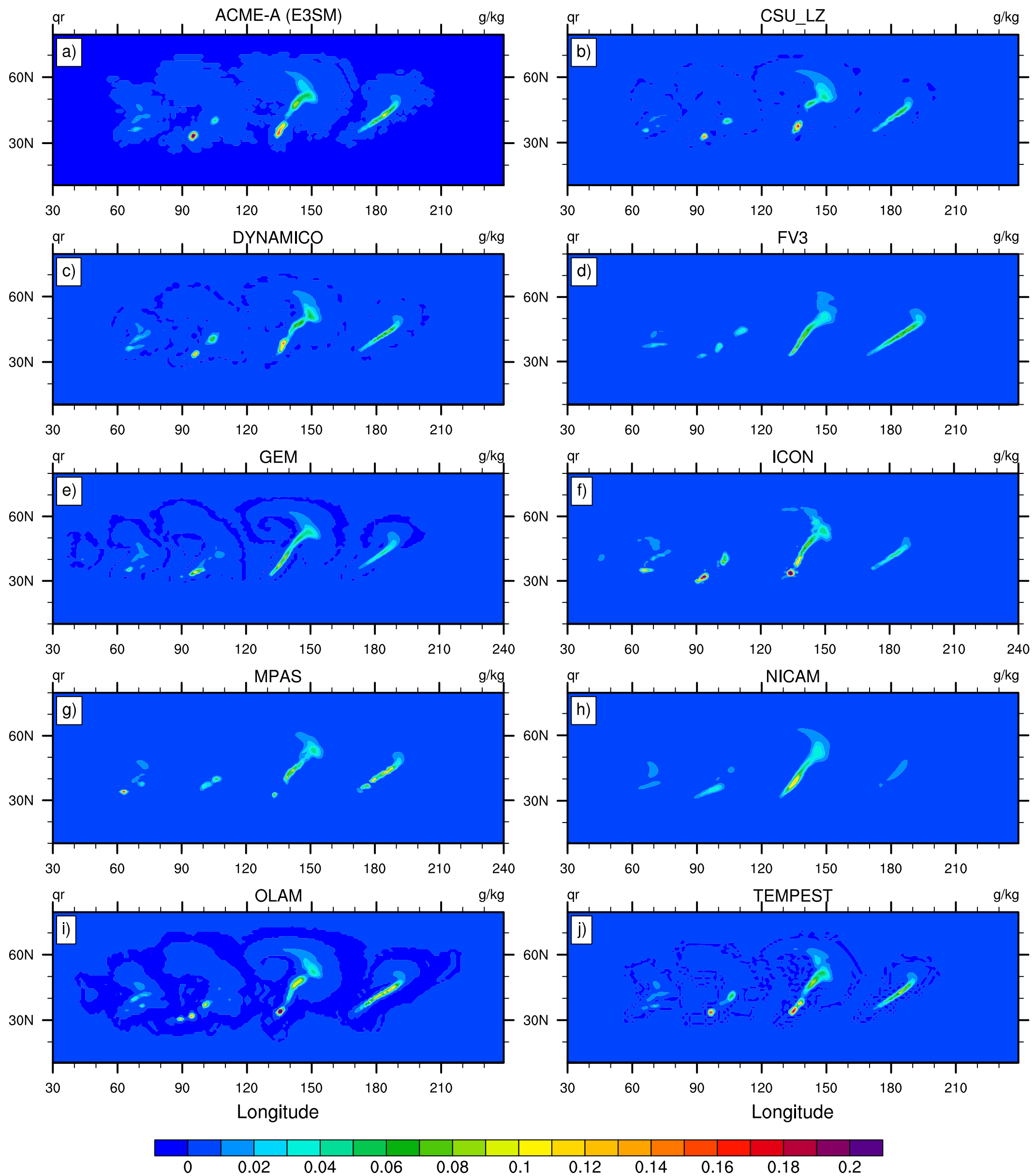
Integrated cloud water: moist baroclinic wave



Vertically integrated cloud water at day 10
(Δx=110 km)

- Cloud water highlights the physics-dynamics interactions
- Generation of cloud water is not resolved, parameterized in the Kessler warm rain scheme
- Model differences become more apparent

Integrated rain water: moist baroclinic wave

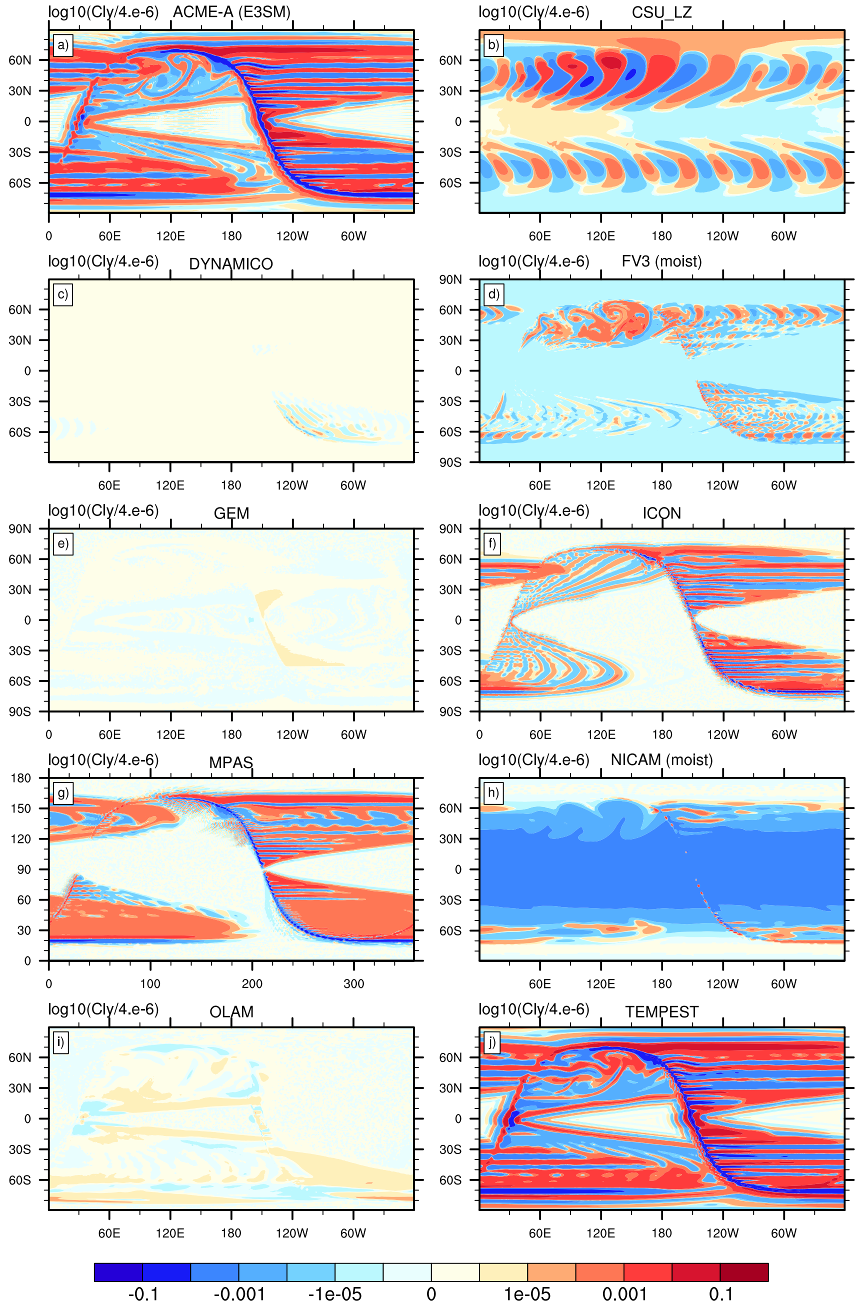


Vertically integrated rain water at day 10

(Δx=110 km)

- Rain water further highlights the physics-dynamics interactions
- Rain water comes from cloud water pool, parameterized in the Kessler scheme
- Differences become even more apparent
- Coherent patterns break up for this metric

Tracer consistency in the dry baroclinic wave

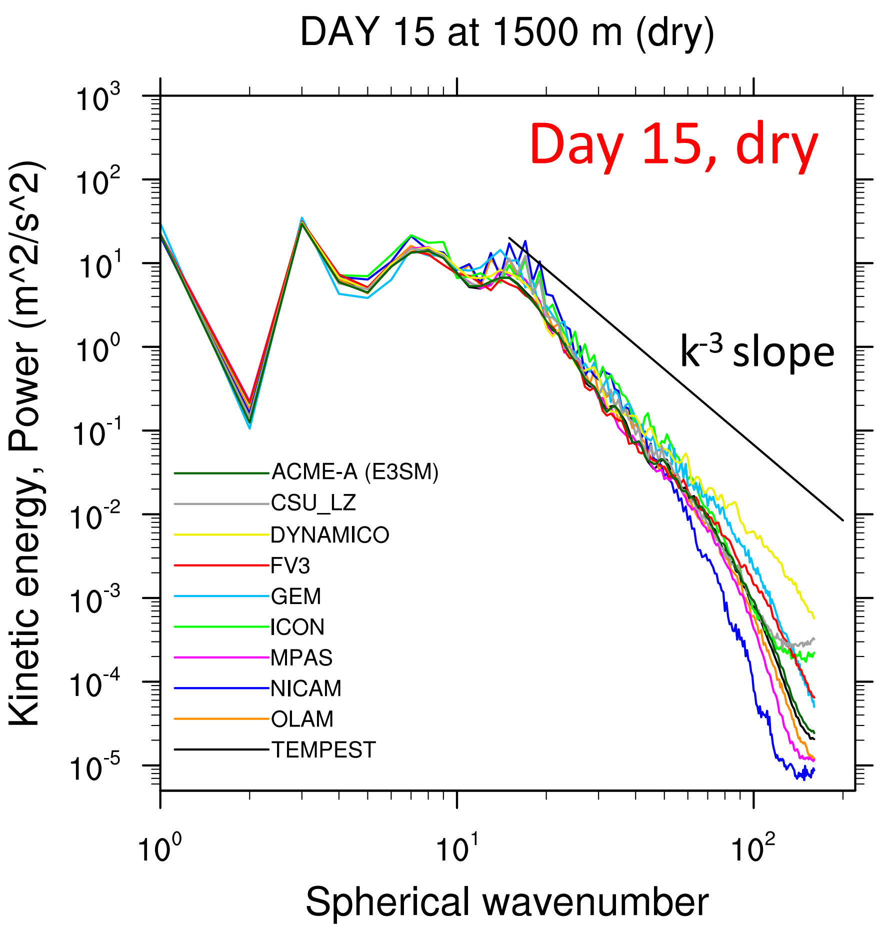


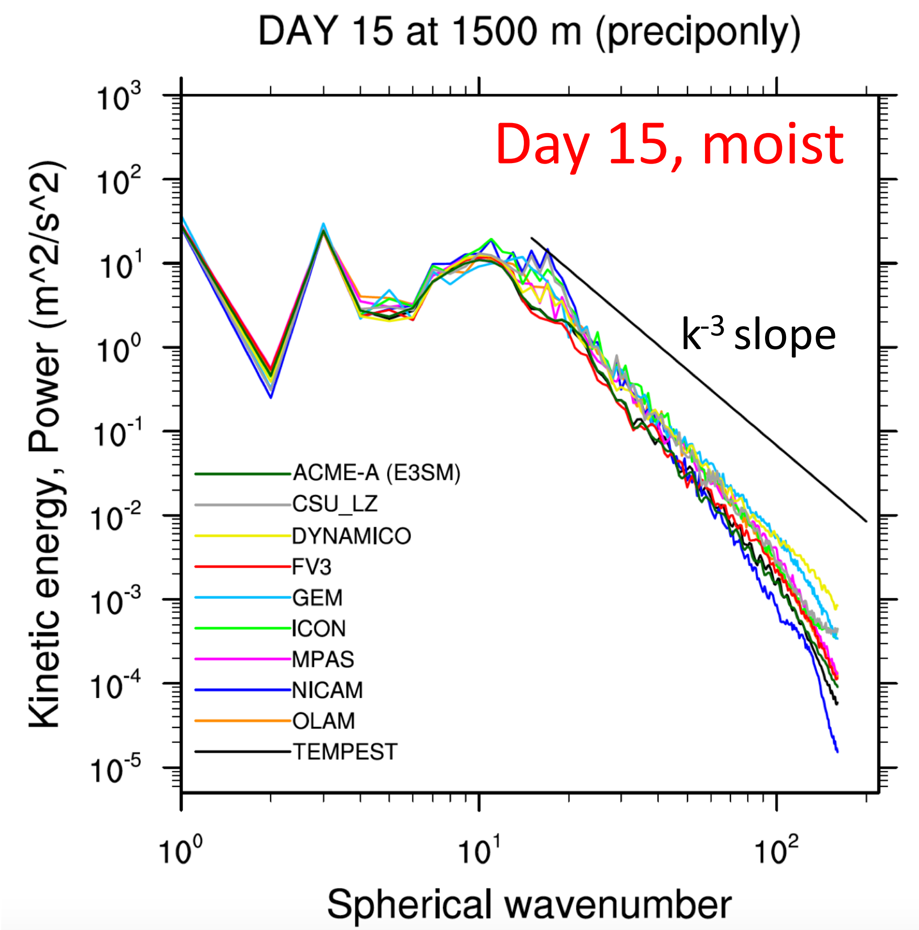
Vertically integrated tracers (weighted sum) at day 10

(Δx=110 km)

- Correlated tracer should stay perfectly correlated
- Analytical solution: zero variations
- Magnitudes of the tracer errors differ greatly (10^{-1} – 10^{-6}), caused by limiters, diffusion and monotonic constraints in the numerics

1500 m Kinetic Energy Spectra: dry and moist

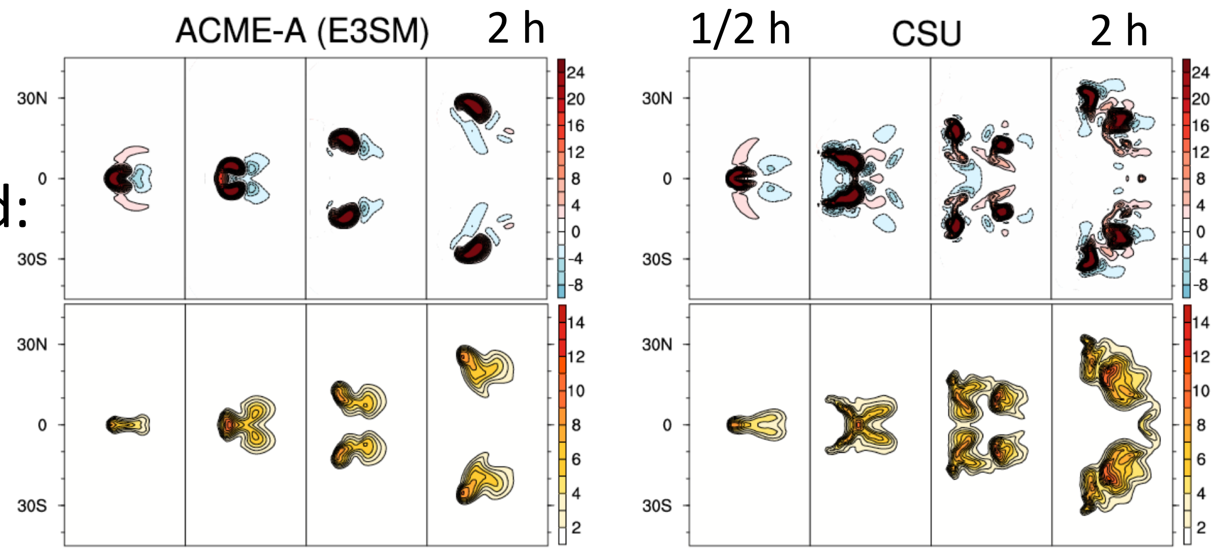




- KE spectra provide information about the diffusion properties
- Some dry dynamical cores flatten their KE spectra
- Despite nominal 1° resolutions, resolved scales vary widely as indicated by the wide spread at high wavenumbers, spread narrows in moist runs

Snapshots: Supercell Simulations (dx=1 km)

Very wide model spread: diffusion processes differ

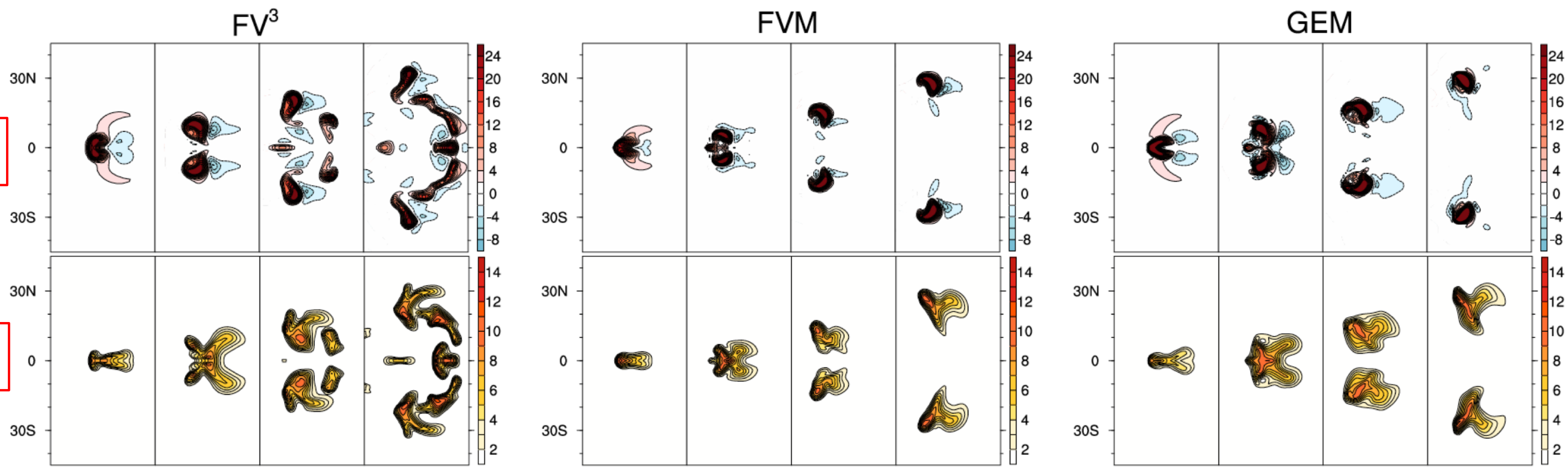


w vertical velocity

q_r rain water

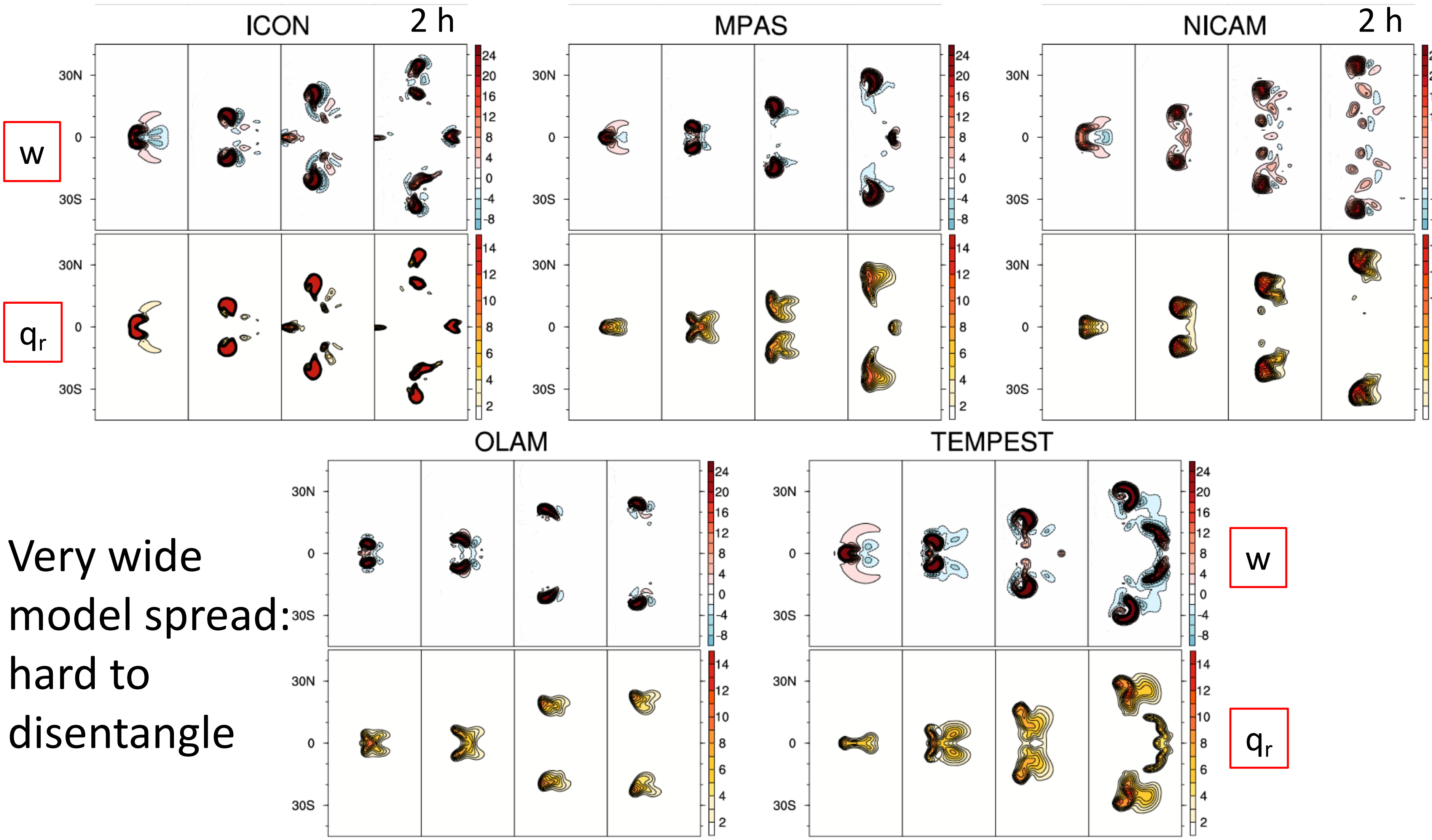
w

q_r



- Time series of vertical velocity (top row) and rain water (bottom row) at 5 km after 30, 60, 90 and 120 minutes (horizontal resolution is 1 km)

Snapshots: Supercell Simulations (dx=1 km)



Very wide model spread: hard to disentangle

- Time series of vertical velocity (top rows) and rain water (bottom rows) at 5 km after 30, 60, 90 and 120 minutes (horizontal resolution is 1 km)

Conclusions

- The interactions between a dynamical core and moisture processes can already be simulated with very simple model configurations, like the Kessler warm-rain scheme
- Rich data base: moist dynamical core configurations reveal aspects of the physics-dynamics coupling, related to different dynamical cores, resolutions and physics time steps
- Idealized test cases are a useful tool (with quick turn around times) to test/understand the moisture aspects
- Causes and effects can be analyzed more easily, but are still difficult to disentangle
- We currently further analyze the impact of various numerical & diffusion choices and physics-dynamics coupling decisions (e.g. Δt)

References

Lauritzen, P. H., A. J. Conley, J.-F. Lamarque, F. Vitt, and M. A. Taylor (2015): **The terminator "toy"-chemistry test: A simple tool to assess errors in transport schemes,** *Geosci. Model Dev.*: 8, 1299-1313, doi:10.5194/gmd-8-1299-2015

Reed, K. A. and C. Jablonowski (2012): **Idealized tropical cyclone simulations of intermediate complexity: a test case for AGCMs**. *J. Adv. Model. Earth Syst.*, Vol. 4, M04 001, doi:10.1029/2011MS000099

Ullrich, P. A., T. Melvin, C. Jablonowski and A. Staniforth (2014): **A proposed baroclinic wave test case for deep- and shallow-atmosphere dynamical cores**. *Quart. J. Royal Meteor. Soc.*, Vol. 140, 1590-1602, doi: 10.1002/qj.2241

Ullrich, P. A. et al. (2017): DCMIP2016: a review of non-hydrostatic dynamical core design and intercomparison of participating models. *Geosci. Model Dev*, Vol. 10, 4477–4509, doi: 10.5194/gmd-10-4477-2017

Zarzycki, C. M., C. Jablonowski, J. Kent, P. H. Lauritzen, R. Nair, K. A. Reed, P. A. Ullrich, D. M. Hall, D. Dazlich, R. Heikes, C. Konor, D. Randall, X. Chen, L. Harris, M. Giorgetta, D. Reinert, C. Kühnlein, R. Walko, V. Lee, A. Qaddouri, M. Tanguay, H. Miura, T. Ohno, R. Yoshida, S.-H. Park, J. Klemp, and W. Skamarock (2019), **DCMIP2016: The Splitting Supercell Test Case,** Geosci. Model Dev., Vol. 12, 879–892

DCMIP-2016 project page:
https://www.earthsystemcog.org/projects/dcmip-2016/